APPLICATION

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TITLE: INTERFEROMETRIC SERVO CONTROL SYSTEM FOR STAGE METROLOGY

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INTERFEROMETRIC SERVO CONTROL SYSTEM FOR STAGE METROLOGY

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority from provisional application serial number 60/252,108 entitled "Interferometric servo control system for stage metrology" by Henry A. Hill and filed November 20, 2000. The contents of the provisional application are incorporated herein by reference.

BACKGROUND

Microlithography and electron beam writing are examples of applications that generate precise patterns on a sample, such as a semiconductor wafer or mask. Such applications require accurate placement and/or movement of the sample stage relative to the writing tool. Often, accurate positioning of different components within the writing tool, such as the relative position of a reticle in a lithography tool, also requires accurate positioning.

To enable such accurate positioning, heterodyne distance measuring interferometers are often used to measure distance changes along one or more axes. The distance measurements can provide a control signal that drives a servo system for accurately positioning different components of a given system.

A heterodyne distance measuring interferometer measures changes in the position of a measurement object relative to a reference object based on optical interference generated by overlapping and interfering a measurement beam reflected from a measurement object with a reference beam. Measurement of the optical interference produces an interference intensity signal that oscillates at a heterodyne angular frequency ω corresponding to small difference in frequency between the measurement and reference beams. Changes in the relative position of the measurement object correspond to changes in the phase φ of the oscillating intensity signal, with a 2π phase change substantially equal to a distance change L of $\lambda/(np)$, where L is a round-trip distance change, *e.g.*, the change in distance to and from a stage that includes the measurement object, λ is the wavelength of the measurement and reference beams, n is the refractive index of the medium through which the light beams

travel, *e.g.*, air or vacuum, and p is the number of passes to the reference and measurement objects.

Unfortunately, this equality is not always exact. Many interferometers include non-linearities such as what are known as "cyclic errors." Some cyclic errors can be expressed as contributions to the phase and/or the intensity of the measured interference signal and have a sinusoidal dependence on the change in optical path length pnL. In particular, the first harmonic cyclic error in phase has a sinusoidal dependence on $(2\pi pnL)/\lambda$ and the second harmonic cyclic error in phase has a sinusoidal dependence on $2\cdot(2\pi pnL)/\lambda$. Higher order and sub-harmonic cyclic errors can also be present.

SUMMARY

The invention relates to metrology systems in which an interferometric measurement provides a control signal for a servo system that positions a device, such as a lithographic stage. The applicant has recognized that, in the absence of any cyclic error compensation, cyclic errors in the interferometric measurement are a source of a false error signal in the servo system and can cause deviations in the desired position of the device, e.g., stage oscillations. In particular, depending on properties of the complex open-loop gain of the servo system as a function of frequency, the deviations can comprise oscillations with amplitudes that are either as large as the magnitude of the cyclic error(s) in the interferometric measurement or significantly exceed the magnitude of the cyclic error(s). Such deviations, however, provide an observable for identifying and quantifying such cyclic errors. The quantified cyclic errors can be used to generate a compensation signal that corrects the interferometric control signal and thereby eliminating the source of the false error signal in the servo system and improves the accuracy of the stage metrology system.

In general, in one aspect, the invention features a method for determining nonlinear cyclic errors in a metrology system that positions a measurement object (e.g., a stage in a lithography or beam writing tool) under servo-control based on an interferometrically derived position signal. The method includes: translating the measurement object under servo-control at a fixed speed; identifying frequencies of any oscillations in the position of measurement object as it is translated at the fixed speed; and determining amplitude and

phase coefficients for a sinusoidal correction term at one of the identified frequencies which when combined with the position signal suppress the oscillations at that frequency.

Embodiments of the method may further include any of the following features.

The method may further include the steps of: repeating the translating, identifying, and determining steps for each of multiple, additional fixed speeds; and generating a representation of the nonlinear cyclic errors based on the coefficients and identified frequencies corresponding to the oscillations at each of the fixed speeds.

In some embodiments, the interferometrically derived position signal is the phase of an interferometric intensity signal at a heterodyne frequency. In other embodiments, the interferometrically derived position signal is a heterodyne, interferometric intensity signal.

To combine the sinusoidal correction signal with the position signal, the sinusoidal correction term may be, for example, subtracted from or added to the position signal to suppress the oscillations.

In general, in another aspect, the invention features a method for positioning a measurement object (e.g., a stage in a lithography or beam writing tool) under servo-control based on an interferometrically derived position signal indicative of a position for the measurement object. The method includes: generating a compensated position signal based on the interferometrically derived position signal and at least one correction term that has a sinusoidal dependence on the position of the measurement object; and repositioning the measurement object based on the compensated position signal and a desired position for the measurement object.

Embodiments of the method may include any of the following features.

For example, the generation of the compensated position signal may include: determining a speed for the measurement object based on the interferometrically derived position signal, and selecting parameters for the at least one sinusoidal correction term based on the determined speed.

The compensated position signal may be generated by subtracting the at least one sinusoidal correction term from the interferometrically derived position signal.

The interferometrically derived position signal may be the phase of an interferometric intensity signal at a heterodyne frequency. Alternatively, the interferometrically derived position signal may be a heterodyne, interferometric intensity signal.

The at least one sinusoidal correction term may include multiple sinusoidal correction terms (e.g., two, three, or more such terms). Each of the multiple sinusoidal correction terms may correspond to a cyclic error in the interferometrically derived position signal.

In general, in another aspect, the invention features an electronic processing system for use with a servo-system for positioning a measurement object. The electronic processing system includes: an input port configured to receive a position signal from an interferometry system indicative of a position for the measurement object; a memory storing a representation of nonlinear errors in the interferometry system; a processor which during operation generates a compensated position signal based on the position signal from the interferometry system and the stored representation; and an output port configured to direct the compensated position signal to a servo-controller.

Embodiments of the electronic processor may include any of the following features.

For example, the stored representation of nonlinear errors may be expressed as a sum of multiple correction terms each having a sinusoidal dependence on the position of the measurement object.

The stored representation of nonlinear errors may be parameterized by a speed of the measurement object. For example, during operation the processor may further determine an estimate for the speed of the measurement object based on the position signal from the interferometry system, and generate the compensated position signal based on the position signal from the interferometry system, the stored representation of nonlinear errors, and the estimated speed.

Other features, objects, and advantages of the invention will be apparent from the description and drawings, and from the claims.

DESCRIPTION OF DRAWINGS

FIG. **1** is a schematic diagram of a servo-controlled stage metrology system.

DETAILED DESCRIPTION

The invention features a method for identifying and quantifying cyclic errors in a servo-controlled interferometric metrology system. Once quantified, cyclic errors in the interferometric control signal can be removed to suppress errors that may otherwise cause oscillations in the metrology system because of positive feedback.

Interferometry systems that quantify and compensate for non-linearities, such as a cyclic errors, and the application of such interferometry systems to microlithography and beam writing applications are disclosed in the following U.S. Patent and U.S. Patent Applications, the contents of which are incorporated herein by reference: U.S. Patent No. 6,137,574 to Henry Allen Hill entitled "Systems and Methods for Characterizing and Correcting Cyclic Errors in Distance Measuring and Dispersion Interferometry;" U.S. Patent Application No. 09/557,338 filed April 24, 2000, by Henry Allen Hill entitled "Systems and Methods for Quantifying Nonlinearities in Interferometry Systems;" and U.S. Patent Application No. 09/583,368 filed May 30, 2000, by Henry Allen Hill entitled "Systems and Methods for Quantifying Nonlinearities in Interferometry Systems."

FIG. **1** is a schematic diagram of a stage metrology system **100**, which includes a translatable stage **60** for supporting, e.g., a wafer or reticle in a microlithography tool, a translator **62** for translating stage **60** along an axis, and an interferometer **30** for measuring the translations along the axis.

During operation, source **10** generates an input beam **12** including two coextensive orthogonally polarized components that are frequency-shifted one with respect to the other. In the presently described embodiment, source **10** includes a coherent source of a single frequency optical beam such as a laser and an acousto-optical modulator to generate the two frequency-shifted components of beam **12**. In other embodiments, source **10** can be, for example, a laser source that generates the frequency-shifted components intracavity, such as in a Zeeman-split laser. Input beam **12** is incident on interferometer **30**. One frequency component of beam **12** defines a measurement beam **14** that contacts a mirror **50** connected to stage **60** and is subsequently reflected back to interferometer **130**. The other frequency component defines a reference beam, which interferometer **30** combines with the reflected measurement beam to form an output beam **16**. Interferometer **30** can be any of a number of interferometers, for example, it can be a single-pass dynamic interferometer (see, e.g., PCT application US99/19904 filed August 31, 1999), a double-pass high stability plane mirror interferometer, a double-pass differential plane mirror interferometer, or some other angle or linear displacement interferometer such as those described in the article entitled "Differential interferometer arrangements for distance and angle measurements: Principles, advantages and applications" by C. Zanoni, *VDI Berichte* Nr. **749**, 93-106 (1989).

Referring again to FIG. **1**, mirror **32** reflects output beam **16** to detector **32**, which measures the intensity of the output beam using, for example, a quantum photon process, to produce an electronic interference signal, heterodyne signal **20**. The phase of heterodyne signal **20** is related to the linear displacement of stage **60**. In particular, in the absence of any non-linearities such cyclic errors, signal **20** can be expressed as $s(t)$ where

$$s(t) = a\cos(\omega t + \varphi + \zeta), \tag{1}$$

$$\varphi = Lkn, \tag{2}$$

where L is the linear displacement given by the physical path length difference between the reference and measurement paths, k is the wavenumber of the measurement beam, n is the refractive index within the interferometer, ω is the angular difference frequency between the measurement and reference beams, t is time, a is an amplitude that is constant with respect to φ, and ζ is a phase offset that is constant with respect to φ and $\dot{\varphi}$, where $\dot{\varphi}$ is the first derivative of φ with respect to time. In the subsequent treatment, we set $\zeta = 0$. Detector **32** transmits signal **20** in, e.g., a digital format, to electronic processor **34**, which determines the phase φ of signal **20** by a phase detector using, for example, a fast Fourier transform of signal **20**.

In the presence of non-linearities, however, such as those described in the U.S. Patents and Patent Applications incorporated by reference above, the phase determined by electronic processor **34** is $\varphi' = \varphi + \psi$, where is ψ corresponds to a contribution from non-linearities, which can generally be expressed as:

$$\psi = \sum_n A_n \cos(\omega_n t + p_n \varphi + \zeta_n) \tag{3}$$

where A_n, ζ_n, ω_n, and p_n are the amplitude, phase offset, frequency, and harmonic index, respectively, of the nth nonlinear term. The harmonic index p_n can take on integer and fractional values. Also, for many nonlinear terms, the frequency ω_n is zero. For example, the first harmonic cyclic error corresponds to a value of one for p_n and a value of zero for

ω_n. As described in the U.S. Patents and Patent Applications incorporated herein by reference above, other types of cyclic errors, such as non-linearity in detector **32** and aliasing effects, can produce additional values for p_n such as sub-harmonic values and frequencies dependent upon the sampling frequency of an analog-to-digital converter used in conversion of $s(t)$ to a digital format. Furthermore, the amplitude and phase of each nonlinear term often varies with the speed of the stage, which is related to the instantaneous rate of change of phase φ, denoted as $\dot{\varphi}$.

Electronic processor **34** sends a signal **22** indicative of the determined phase φ' to both electronic processors **36** and **38**. Electronic processor **36** stores a quantified representation of at least one or some of the non-linearities generally present in the interference signal because of imperfections in interferometer **30**. For example, electronic processor **36** can store values of the nonlinear coefficients A_n, ζ_n, ω_n, and p_n for at least one or some of the nonlinear terms, which permit it to estimate the value of ψ from the value of φ' in signal **22**. Such determination can, for example, involve an iterative calculation of ψ based on the initial assumption that $\varphi \approx \varphi'$.

Where necessary, electronic processor **36** also stores the stage speed dependence of the quantified non-linearities. For example, the amplitude and phase estimates stored by electronic processor **36** for the nonlinear coefficients can be parameterized with respect to $\dot{\varphi}$, in other words, the stored estimates can be indicative of $A_n(\dot{\varphi})$ and $\zeta_n(\dot{\varphi})$. In such embodiments, electronic processor **34** determines values for the phase φ, and its instantaneous rate of change $\dot{\varphi}$, and sends both values to electronic processor **36** as signal **22**. Electronic processor **36** then approximates $\dot{\varphi} \approx \dot{\varphi}'$ to determine the stage speed dependence of $A_n(\dot{\varphi})$ and $\zeta_n(\dot{\varphi})$, or alternatively, determines $\dot{\varphi}$ from $\dot{\varphi}'$ in an iterative process. In other embodiments, electronic processor **36** can receive an additional input from an independent source that monitors the stage speed. In any case, electronic processor **36** uses its stored, quantified representation to determine the nonlinear contribution ψ to the phase φ' determined by electronic processor **34**.

Electronic processor **36** sends the determined value for ψ to electronic processor **38** as compensation signal **24**. Electronic process **38** then uses compensation signal **24** to

remove the estimated nonlinear contributions from the measured phase φ' and generate a compensated signal **26** indicative of the phase φ, which is directly related to the stage displacement through Equation 2. Electronic processor **36** sends the compensation signal **26** to servo controller **52**, which compares the stage displacement indicated by signal **26** to the desired stage displacement corresponding to an input control signal **29** to generate a servo signal **28**. Servo controller then sends servo signal **28** to translator **62** to correct any deviation of the translation of the stage **60** from a desired translation time course. Generally, translator **62** may also receive an additional signal (not shown) similar to input control signal **29** (which provides the desired stage translation time course) for coarsely translating stage **60**, with the interferometrically driven servo-system providing fine translation adjustment.

In other embodiments, the representation of the quantified non-linearities in electronic processor **36** can be with respect the intensity of the interference signal rather than its phase at the heterodyne angular difference frequency ω. In such embodiments, the interferometric intensity signal measured by the detector may be expressed as:

$$s'(t) = s(t) + s_{NL}(t) \qquad \textbf{(4)}$$

where $s'(t)$ is the measured intensity, $s(t)$ is the intensity that would be measured in the absence of any non-linearities, and $s_{NL}(t)$ is the nonlinear contribution to the measured intensity. The non-linearities are then expressed as a sum of sinusoidal contributions, e.g.,

$$s_{NL}(t) = \sum_{q} B_q \left\{ \sum_{u,p} a_{up} \cos\left(u\omega t + p\varphi + \zeta_{up}\right) \right\}^{q} \qquad \textbf{(5)}$$

where $p = 1,2,3\ldots$ and fractional values, $u = 0 \texttt{ or } 1$, and $q = 1,2,3\ldots$, and where the "q" index is associated with non-linearity in detector **32**. Thus, in such embodiments, electronic processor **36** can, for example, store the amplitude and phase coefficients for at least one or some of the nonlinear terms in Equation (5) and, where appropriate, their stage speed dependence.

Furthermore, in such embodiments, electronic processor **34** can determine φ' from $s'(t)$ and send $s'(t)$, φ', and $\dot{\varphi}'$ to electronic processor **36** and $s'(t)$ to electronic processor **38** as signal **22**. Electronic processor **36** then determines an estimate for $s_{NL}(t)$ based on the stored, quantified non-linearities and sends that estimate to electronic processor **38** as signal **24**. In turn, electronic processor **38** removes the nonlinear contribution $s_{NL}(t)$ from the measured intensity the measured intensity $s'(t)$ to provide a compensated estimate for $s(t)$, determines the phase φ, which is directly related to the stage displacement through Equation 2, and generates compensated signal **26** indicative of the phase. Electronic processor **38** sends the compensation signal **26** to servo controller **52**, as in the first embodiment.

In any of these embodiments, the quantified representation of non-linearities stored by electronic processor **36** can be determined by any of the methods described in the U.S. Patents and Applications incorporated herein by reference above. They can also be determined through another method described below.

Applicant has recognized that non-linear contributions in signal **26** sent to servo controller **52** can produce a false error signal in the servo system that cause stage oscillations that may be as large as or greatly exceed the amplitude of the non-linear errors in the interferometrically measured displacement.

Consider, for example, a stage translation speed of 25 micron/sec and a double pass interferometer used to measure the corresponding translation and provide the error signal to the servo controller. For this example, the first harmonic cyclic error will have a frequency of 158.0 Hz for a Helium Neon source laser operating at 633 nm, and the one-half sub-harmonic cyclic error will have a corresponding frequency of 79.0 Hz. Both of these frequencies are typically within the bandwidth of the servo system, and can therefore lead to stage oscillations at these frequencies. The cyclic error amplitude required to produce an unacceptable level of stage oscillation will depend on the complex open-loop gain of the servo system. However, cyclic error amplitudes of the order of nanometers may generate an unacceptable level of stage oscillation. Frequencies of cyclic errors that lead to substantially positive feedback in the servo system generate the largest amplitudes in stage oscillation. Such stage translations of the order of 25 micron/sec along an axis can arise during, for example, an alignment procedure. They can also occur during a high-speed translation along

a second axis wherein the stage mirror for the first axis is not orthogonal to the translation axis associated with the second axis by an angle of the order of 100 microradians.

Nonetheless, observation of such stage oscillations provides a method of identifying and quantifying those cyclic errors that produce the stage oscillations.

First, one translates the stage at a fixed speed under closed loop servo control. For example, the stage metrology system **100** is operated with input control signal **29** set for a constant translation speed. If feedback of one or more non-linearities in interferometric signal **20** occurs at that speed, stage oscillations result and correspond to an oscillatory deviation of stage **60** from desired speed at one or more corresponding frequencies. One can measure such deviations from the phase φ' determined by electronic processor **34** because the non-linear error in φ' serving as a false error source will typically be of the order of the stage oscillation amplitude or small compared to the stage oscillation amplitude. Alternatively, one can independently measure the stage oscillations using, e.g., a mechanical or machine vision measurement.

One can then determine the frequency components of oscillatory deviations by Fourier analysis. The resulting frequencies equal the $\omega_n + p_n\dot{\varphi}$ frequencies in Equation (3). For each of these frequencies, electronic processor **36** determines ω_n and p_n by assuming that $\dot{\varphi} \approx \dot{\varphi}'$. Then, for each frequency, electronic processor **36** iteratively determines amplitude A_n and phase offset ζ_n coefficients for a correction term, $A_n \cos\left(\omega_n t + p_n\varphi' + \zeta_n\right)$, which, when subtracted from the measured phase φ' in electronic processor **38**, provides a compensated signal **26** to servo controller **52** that suppresses the stage oscillations at that frequency. Alternatively, the electronic processor can determine the coefficients by adding the correction term to the measured phase, in which case the phase offset ζ_n coefficient will shift by π radians.

Once all of the stage oscillation frequencies have been suppressed, the process is repeated at additional fixed speeds for the stage to determine the frequencies and corresponding amplitude and phase coefficients at each new speed. The resulting frequencies and coefficients are stored in electronic processor **36** to define, or add to, the stored quantified nonlinear representation used during normal operation.

The quantification method can be applied similarly to embodiments where the non-linearities are expressed as sinusoidal contributions to the intensity measured by detector **32**, $s'(t)$.

Other aspects, advantages, and modifications are within the scope of the following claims.

What is claimed is: